ALL-SKY AEROSOL DIRECT FORCING TO SW AND LW AT TOA AND SURFACE USING CERES TERRA AND THE MATCH ASSIMILATION

T.P. Charlock
NASA Langley Research Center, Hampton, Virginia 23681-2199, USA

F.G. Rose and D.A. Rutan
Analytical Services and Materials, Inc., Hampton, Virginia, USA

D.W. Fillmore and W.D. Collins
National Center for Atmospheric Research, Boulder, Colorado, USA

ABSTRACT

A method for computing direct aerosol forcing has been applied to an extensive Terra data set, spanning every second CERES footprint at surface and top-of-atmosphere (TOA). Calculations for the Surface and Atmosphere Radiation Budget (SARB) use cloud properties from MODIS and aerosol properties from MODIS and the MATCH assimilation. Fluxes are routinely compared with completely independent broadband radiometric measurements at approximately 50 ground sites; here reported for March 2000 to December 2001. For 25 March 2000, daily mean all-sky aerosol forcing (SW plus LW) has been estimated as –0.5 Wm-2 at TOA (i.e., aerosols cool the planet), +5.3 Wm-2 for the atmosphere (heating), and –5.9 Wm-2 for the surface net (cooling); the comparable TOA forcing for a theoretically clear ocean is –3.1 Wm-2. The record is publicly available as Terra CERES CRS Edition 2A. Production of a revised set of fluxes and forcings is underway.

1. INTRODUCTION

Direct aerosol forcing is considered as the radiative flux including the effects scattering, absorption, and emission by aerosols, minus the flux without aerosols. The magnitude of direct aerosol forcing – and especially its anthropogenic component – is uncertain (IPCC, 2001). Like trace gases, aerosols affect the planetary radiation balance at TOA. Absorption of SW by aerosols a yields a larger forcing at the surface; this can also potentially spin down the hydrological cycle (i.e., Liepert et al., 2004) and have impacts quite different from those of increased CO2. A climate model simulates the response to a given forcing. In part because we do not know the correct aerosol forcing (natural and anthropogenic) of recent decades, it has not been possible to rigorously validate any model simulation of global mean tropospheric temperature spanning the same interval.

The CERES observations of TOA fluxes (Wielicki, et al., 1997) includes a program to also compute the fluxes at TOA, within the atmosphere and at the surface, and also to validate the results with independent ground based measurements (Charlock and Alberta, 1996). To permit the user to infer cloud forcing and direct aerosol forcing with the computed SARB, CERES includes surface and TOA fluxes that have been computed for cloud-free (clear) and aerosol-free (pristine) footprints; this accounts for aerosol effects (SW and LW) to both clear and cloudy skies.

2. COMPUTATION OF FLUXES

The major inputs to the flux calculation are the instantaneous scene identification; cloud properties from MODIS (Minnis et al., 2002); TOA radiation from the CERES instrument in large (~20 km) footprints; 6-hourly gridded fields of temperature, humidity, wind (GEOS4); and ozone from NCEP (Yang et al., 2000). Aerosol information is taken from MODIS and from the NCAR Model for Atmospheric Transport and Chemistry (MATCH), an assimilation that here also employs aerosol retrievals from MODIS (Fillmore et al. 2005). The archive includes flux profiles calculated by algorithms that partially constrain to CERES TOA observations; and the "untuned" fluxes first calculated by the original inputs. Forcings based on the untuned record are used here.

We use a fast, plane parallel correlated-k radiative transfer code (Fu and Liou, 1993, Fu et al., 1998, 1999) which has been highly modified. A 2 stream calculation is used for SW. LW employs a 2/4 stream version, wherein the source function is evaluated with the quick 2-stream approach, while radiances are effectively computed at 4 streams. Constituents for the thermal infrared include H2O, CO2, O3, CH4 and N2O. A special treatment of the CERES 8.0-12.0 µm window includes CFCs (Kratz and Rose, 1998) and uses the Clough CKD 2.4 version of the H2O continuum. In collaboration with Dr. Qiang Fu, the code was modified to include 10 separate bands between 0.2-0.7 µm. In cooperation with Dr. Seiji Kato,, we have included the HITRAN2000 data base for the determination of correlated k's in the SW (Kato et al., 1999). We make a first order accounting for inhomogeneous cloud optical thickness (using the gamma weighted two stream approximation of Kato et al., 2004) in the SW, fitting a 13-

element histogram of cloud optical thickness in each footprint. An external mixture of aerosols, clouds, and gases is assumed. All-sky aerosol forcing is determined by running with clouds (if present), gases, and aerosols, and subtracting the flux from a run with no aerosols. A theoretical clear-sky aerosol forcing is computed for all footprints as the difference of the cloud-free flux with aerosols minus the cloud-free flux with no aerosols. Aerosol forcing includes the effects scattering (SW and LW), absorption (SW and LW) and emission (LW) by aerosols.

Land surface albedo is explicitly retrieved for clear footprints using a quick table look-up to the Langley Fu-Liou code that relates observed CERES TOA albedo, surface albedo, solar zenith angle (SZA), precipitable water, and aerosol optical thickness (AOT). The spectral shape of the surface albedo is assumed as per the International Geophysical Biospherical Project (IGBP) land type (see http://www-surf.larc.nasa.gov/surf). When cloudy, the land surface albedo is taken from a gridded record of clear-sky retrievals during the same month; and adjusted to account for an effective diffuse SZA beneath clouds. Ocean spectral albedo is obtained using a look up table (LUT) based on discrete ordinate calculations with a sophisticated coupled ocean atmosphere radiative transfer code (Jin et al, 2004). Inputs for ocean spectral albedo include SZA, wind speed, chlorophyll concentration (which has a minor effect on broadband flux), and SW optical depth of clouds and aerosols. There is an empirical correction for surface foam based on wind speed.

AOT is taken from MODIS (MOD04 described by Kaufman et al., 1997) when available. Over the ocean, MOD04 is used for 7 wavelengths; the AOT is interpolated to the remainder of the spectrum using the selected aerosol type, as specified below. Over the land, MOD04 provides AOT at 3 wavelengths, and the MOD04 Angstrom exponent is used to guide the extension over the spectrum. If the MOD04 instantaneous AOT is not available (i.e., footprint is overcast), we temporally interpolate from a file of the MODIS Daily Gridded Aerosol. When cloudiness in the footprint exceeds 50%, or when there is no MODIS AOT, we use AOT from the NCAR MATCH. When AOT is taken from MATCH, we assume it for one wavelength only (0.63µm). MATCH AOT is apportioned to 7 types (small dust, large dust, soot, soluble organic, insoluble organic, sulfate, and sea salt) on a daily basis over the globe for all sky conditions. The Terra CERES CRS Edition 2A results described here assume a global climatological scale height for each of the 7 aerosol types. [A subsequent Edition 2B uses explicit height profiles for the 7 types that vary for each gridbox, each day.]

Aerosol type is always taken from MATCH; this guides the selection of the asymmetry factory (g) and the single scattering albedo (SSA). Asymmetry factors and SSA are assumed from the Tegen and Lacis (1996) and OPACS-GADS (Hess et al., 1998) models.

Reading Dubovik et al. (2002) on AERONET, we infer that the dust optical properties we have selected may be too strongly absorbing. [The subsequent Edition 2B results, which are not plotted in Fig. 1-3 below, use updated optical properties for dust, from A. Lacis of NASA GISS.]

3. VALIDATION OF FLUXES AT SGP

How credible are the computed surface fluxes? The web site http://www-cave/larc.nasa.gov/cave / (search for "CERES CAVE") is a gateway to a point and click version of the radiative transfer code used here; time series of subset results at selected sites; and compares the surface fluxes retrieved by CERES with independent measurements at over 50 sites scattered around the globe (Rutan et al, 2001). Fig. 1 shows the bias (computed minus observed) for a cluster of 22 Atmospheric Radiation Measurement (ARM) sites in the Southern Great Plains (SGP). The absolute magnitudes of biases in Fig. 1 for clear sky (those footprints screened as cloud free by MODIS) are small and generally less that the corresponding magnitudes for clear-sky aerosol forcing in Fig. 2. This gives confidence in the clear-sky forcing to SW insolation, which has a peak during summer at SGP.

Figure 1. Bias (computed minus observed) in surface insolation (monthly mean of daylight SGP overpasses)

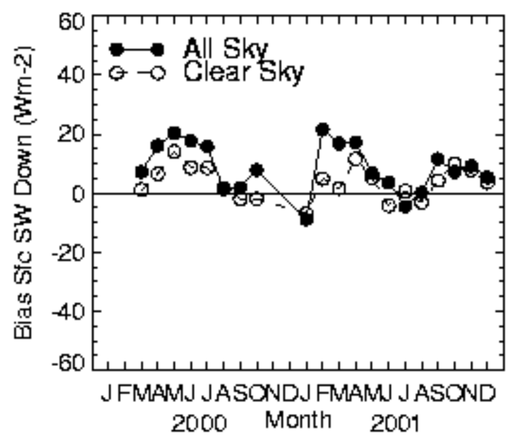
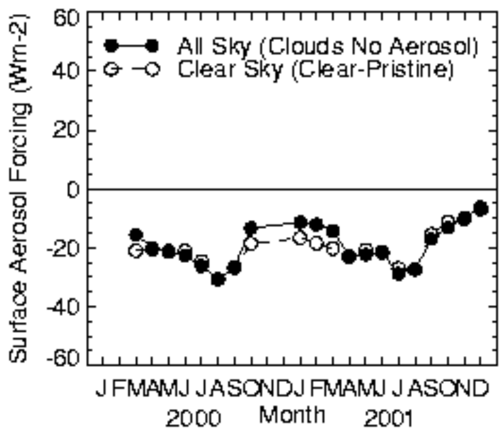


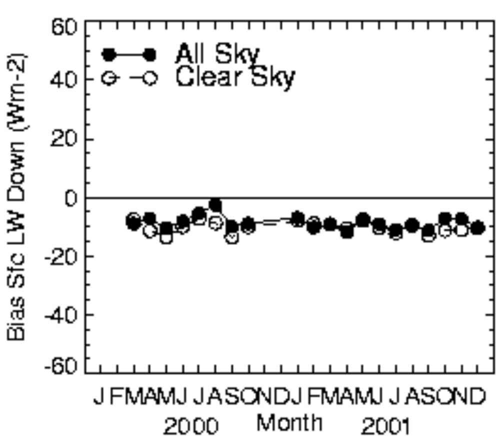
Figure 2. Aerosol forcing to surface insolation (monthly mean of daylight SGP overpasses)



The insolation at all "CAVE" sites (not just SGP) for 2001 gave results similar to Figs. 1 and 2. For all sites, the mean all-sky (clear-sky) observed insolation for daytime Terra overpass was 482.6 Wm-2 (713.3 Wm-2), bias was 7.5 Wm-2 (-5.6 Wm-2), and aerosol forcing –10.7 Wm-2 (-15.3 Wm-2).

Returning to only the SGP sites, we consider surface downward LW flux (DLF), which has a smaller range of variation than does surface insolation. The bias for clear-sky DLF in Fig. 3 is somewhat disappointing. The DLF bias due is due, in turn, to a bias in the surface air temperature inputs from GEOS4. However, the all-sky DLF bias is no larger than the clear-sky DLF bias, attesting to the high fidelity of the cloud property inputs from Minnis et al. (2002).

Figure 3. Bias (computed minus observed) in surface DLF (monthly mean of day and night SGP overpasses)



4. GLOBAL FORCING FOR 1 DAY

The aerosol forcing for the approximately two million CERES footprints on 25 March 2000 in Table 1 have been weighted, to compensate for the differing sizes of the footprints and the increased frequency of sampling at higher latitudes. Table 1 estimates 24-hour mean forcing as a simple average of Terra overpasses, which occur at ~1030 L and ~2230 L over most of the globe. Net flux in Table 1 is taken as downwelling minus upwelling; the atmosphere forcing is the forcing to TOA net minus the forcing to surface net. To facilitate a diagnosis of the effects of clouds on aerosol forcing, Table 1 uses the designation "as if clear" for a theoretically clear forcing, which is computed whether or not the footprint is clear or cloudy. This is different than the "clear" qualification in Figs. 1, 2, 3, wherein clear denotes the subset of footprints that have been screened as cloud free by MODIS. Clouds substantially reduce TOA aerosol forcings but have proportionately less effect on the larger aerosol forcing to the atmosphere, which ultimately affects the hydrological cycle. The substantial atmosphere forcing to all-sky global SW plus LW (5.3 Wm-2 in Table 1) has been significantly reduced from the SW only value (6.6 Wm-2) by atmosphere cooling due to LW (-1.3 Wm-2).

Table 1. Global aerosol forcing on 25 March 2000 as mean of Terra overpasses (~1030 L and ~2230 L)

SW Aerosol Forcing (Wm-2)

level	Globe	Globe as if clear	Ocean	Ocean as if clear
TOA Net	-1.1	-2.6	-2.2	-3.6
Atmosphere	6.6	6.9	3.2	3.3
Surface Net	-7.7	-9.4	-5.4	-6.9

LW Aerosol Forcing (Wm-2)

level	Globe	Globe as if clear	Ocean	Ocean as if clear
TOA Net	0.6	0.8	0.3	0.5
Atmosphere	-1.3	-1.9	-0.7	-1.4
Surface Net	1.8	2.7	1.0	1.8

SW+LW Aerosol Forcing (Wm-2)

level	Globe	Globe as if clear	Ocean	Ocean as if clear
TOA Net	-0.5	-1.8	-1.9	-3.1
Atmosphere	5.3	5.0	2.5	1.9
Surface Net	-5.9	-6.7	-4.4	-5.1

5. DISCUSSION OF FORCINGS

A comparison of the biases in surface insolation (Fig. 1) and values of respective aerosol forcings (Fig. 2) suggests that the CERES SARB clear-sky forcing to insolation may be accurate over SGP to within a factor of two. More detailed study is needed to rigorously judge the corresponding forcings to all-sky insolation. This is certainly the case for aerosol forcing to DLF, which is small relative to the bias in Fig. 3.

What is the quality of the retrieved forcing displaced from SGP, as over the whole globe in Table 1? Note that all results mentioned to this point use "Edition 2A" scale heights for aerosols; and the older Tegen and Lacis properties for dust (when present). The more sophisticated treatment of both in the coming Edition 2B yields substantial changes for SW forcing: All-sky global SW TOA forcing is –1.1 Wm-2 (-2.5 Wm-2) in Edition 2A (2B); and corresponding SW surface forcings are –7.7 Wm-2 (-6.6 Wm-2) in Edition 2A (2B). These large changes (Edition 2A to 2B) point to the importance of dust optical properties over the globe. In contrast, relatively little dust is found over SGP (Figs. 1-2). Uncertainties in the optical properties of dust are likely to challenge the estimation of direct aerosol forcing to the global atmosphere and hydrological cycle for some time.

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Thomas P. Charlock Thomas.P.Charlock@nasa.gov
Mail Stop 420
NASA Langley Research Center
Hampton, Virginia 23681-2199 USA
Phone 1-757-864-5687 Fax 1-757-864-7996

KEY WORDS

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LW (longwave)
aerosol
direct forcing
top-of-atmosphere (TOA)
MODIS
GEOS4
Terra CERES CRS
Surface and Atmosphere Radiation Budget (SARB)
anthropogenic
planetary radiation budget
hydrological cycle
Model for Atmospheric Transport and Chemistry (MATCH)
correlated-k
2 stream
2/4 stream
inhomogeneous cloud

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land surface albedo
solar zenith angle (SZA)
ocean spectral albedo
asymmetry factor (g)
single scattering albedo (SSA)
OPAC-GADS
surface insolation
surface insolation

Page 3:

surface downward LW flux (DLF)